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Sustainable silicon photovoltaics manufacturing in a global market: A techno-economic, tariff and transportation framework

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HIGHLIGHTS

- A framework to optimize photovoltaics manufacturing supply chains is proposed.
- Techno-economic, transportation, and tariff variables impact supply chain results.
- Multiple objectives can be optimized while achieving low PV manufacturing costs.
- Minimum sustainable price is substantially increased upon tariffs introduction.

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ABSTRACT

Solar photovoltaics (PV) manufacturing has experienced dramatic worldwide growth in recent years, enabling a reduction in module costs, and a higher adoption of these technologies. Continued sustainable price reductions, however, require strategies focused in further technological innovation, minimization of capital expenditures, and optimization of supply chain flows. We present a framework: Techno-economic Integrated Tool For Tariff And Transportation (TIT-4-TAT), that enables the study of these different strategies by coupling a techno-economic model with a tariff and transportation algorithm to optimize supply chain layouts for PV manufacturing under equally-weighted objectives.

We demonstrate the use of this framework in a set of interacting countries (Mexico, China, USA, and Brazil) and two extreme tariff scenarios: no tariffs, and high tariff levels imposed. Results indicate that introducing tariffs between countries significantly increase the minimum sustainable price for solar PV manufacturing, alter the optimal manufacturing locations, and render a more expensive final solar PV module price which can hinder the adoption rates required to mitigate climate change. Recommendations for stakeholders on the optimization process, and techno-economic drivers are presented based on our results. This framework may be utilized by policymakers for the spatially-resolved planning of incentives, labor and manufacturing programs, and proper import tariff designs in the solar PV market.

1. Introduction

In an effort to mitigate climate change, an increased number of countries are aligning their investment strategies and incentives towards decarbonizing different sectors of their economies [1–6]. This ongoing transition has led to a global surge in the commissioning of renewable energy projects with solar photovoltaic (PV) technologies representing a significant percentage of the total [7].

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The increase in adoption of solar PV technologies has been driven, to a significant degree, by the enactment of policies that mandate a higher penetration of clean energy sources in the energy mix. The increased rate of adoption has also led to a price drop in excess of 80% in the last 6 years [8], with expectations of further price reductions in the near future [9,10]. Given the expected market growth in global solar PV, firms must compete to serve both existing and new markets at least cost.

Despite current oversupply conditions [11], the cyclic nature of the crystalline silicon photovoltaics (c-Si PV) industry is still a driver for some countries to plan ahead and analyze their options for investing –both directly and indirectly– in developing a local manufacturing base for some or all segments of the PV value chain, as adequate long-term planning policy designs help mitigate volatility risks.

Across many different industries, developing a local, specialized manufacturing base has been shown to bring positive effects, such as knowledge spillovers, where existing firms can benefit from sharing knowledge and human capital, even if not employing the same technology [12]. Geographic proximity between firms and research institutions can enhance the sharing of knowledge in both directions, and can help accelerate R&D cycles and local implementation of technology [13], potentially lowering manufacturing and deployment costs. And through the optics of potential levers to improve environmental conditions, industrial supply chains have been identified as key components for reducing regional carbon footprints and energy use [14].

To continue achieving sustainable price reductions in c-Si PV manufacturing, different strategies can be adopted at different levels. Starting at the module level, technological innovation in material growth conditions can lead to higher conversion efficiencies at least cost [15]. At the facility level, minimizing capital expenditures (capex) has been identified as one of the main drivers in lowering c-Si PV prices [16]. At a market level, optimizing the supply chain flow can lead to reduced factory capex, reduced activity cycle times, and increased demand flexibility [17]. To maximize impact, all these strategies often have to occur simultaneously.

Tariffs are commonly implemented to provide protection to infant industries while they become strong enough to compete in other countries. These measures, however, tend to be over-extended in some instances, turning into long-term corporate welfare, reducing national welfare as a whole by only benefitting interest groups [18,19].

Techno-economic models, whether for installation and operation [20–24], or manufacturing [25–27], can elucidate the variables of merit with highest potential to reduce costs. Recent efforts have been aimed at expanding the impact of these models by broadening the range of the studied supply chains and their carbon emissions [28]. However, these approaches lack the ability to incorporate interactions among various regions in the world, and the impact of tariff levels on supply chain configurations, both relevant and applicable to current real-world situations where financial and environmental impacts need to be contemplated.

In the attempt to develop a quantitative approach for the optimal siting of PV manufacturing supply chains, accounting for financial and environmental objectives, this study introduces a framework to simultaneously analyze all three described levels (module, facility, market) by pairing a cost model with a transportation and import/export tariff model. The techno-economical model for c-Si PV, developed by [29], estimates the minimum sustainable prices (MSP) required to financially sustain a manufacturer at different c-Si PV segments. The transportation and tariff model presented optimizes the geographic steps that render the optimal overall supply chain route considering diverse objectives such as local MSP, transportation costs, and import/export tariffs: from polysilicon, to ingot, to wafer, to cell, and to module assembly, prior to shipping to end destinations.

To demonstrate the applicability of this methodology, we then adapt this coupled model to a case study for Mexico. Mexico was selected based on its ample manufacturing base, number of international treaties, reported economic competitiveness (moderate wage growth, sustained productivity gains, and energy cost advantages), and geographic proximity to North, Central, and South American markets [30]. The authors recognize that many other geographies with PV manufacturing potential also exist, and the proposed methodology can also be implemented in other countries.

We conclude with policy recommendations based on the results for the case of PV manufacturing, given the developed scenarios. We demonstrate that upon a tariff implementation, manufacturing costs in Mexico rise up more than 200%, disrupting supply chains and potentially hindering PV deployment growth, all else equal.

Our proposed framework aims to serve as a tool to support data-driven, strategic decisions in developing local PV manufacturing clusters, as well as to identify the specific drivers that would have the highest impact if modified in a global supply chain context.

2. Material and methods

2.1. Design outlay elements of crystalline silicon photovoltaics supply chain

For the purpose of this analysis, we segment the PV supply chain into five manufacturing and processing steps: (i) polysilicon, (ii) ingot, (iii) wafer, (iv) cell, and (v) module production.

Details on each of these manufacturing and processing steps have been extensively reported in literature [31–35], and herein we merely provide a brief summary of these steps.

Producing polysilicon for PV applications can be done using different methods with varying levels of energy intensity and product purity [36]. The common denominator for this process is the raw material requirement –specifically, quartz– and high temperature processing with coke to produce metallurgical Si (MG-Si), before being transformed into higher purity silicon through one of various processes such as Siemens or fluidized bed reactor, among others [36–39].

For silicon photovoltaic applications, monocrystalline material grown from the Czochralski (Cz) method has consistently been used to develop higher efficiency solar cells, compared to alternative materials, like multi-crystalline silicon [40–43]. In the Cz method, a seed crystal of silicon is dipped into and slowly withdrawn from a crucible containing melted silicon, creating a solidified single crystal as the end product [44,45]. Crystal rods are then cut into wafers, typically through multi-wire sawing [46]. Next, surface texturing and anti-reflection coating deposition is performed to enhance light capturing [47–50]. Metal contacts are then typically printed and fired to convert the wafer into a working solar cell device [51,52]. Finally, solar cells are interconnected, encapsulated, and assembled into a module capable of generating power [53].

2.2. Minimum sustainable price

To estimate the cost for each of the five manufacturing steps previously described, we use the MSP model [54]. The MSP model estimates the minimum price ($/W) at which a manufacturer can financially sustain the production and selling of a good by equating its weighted average cost of capital (WACC) to its internal rate of return (IRR) [14,42].

Using this methodology, we simulate a cash flow for a hypothetical manufacturer located either at a state within the country of interest, or at a city within the country if the latter is considered for import and export interactions. Through this cash flow, we compute the price of the product when the net present value is equal to zero. The MSP calculations, which consider operating costs, investment costs, inflation, and depreciation, are performed by using and modifying the values in the open-access spreadsheet published in [56].

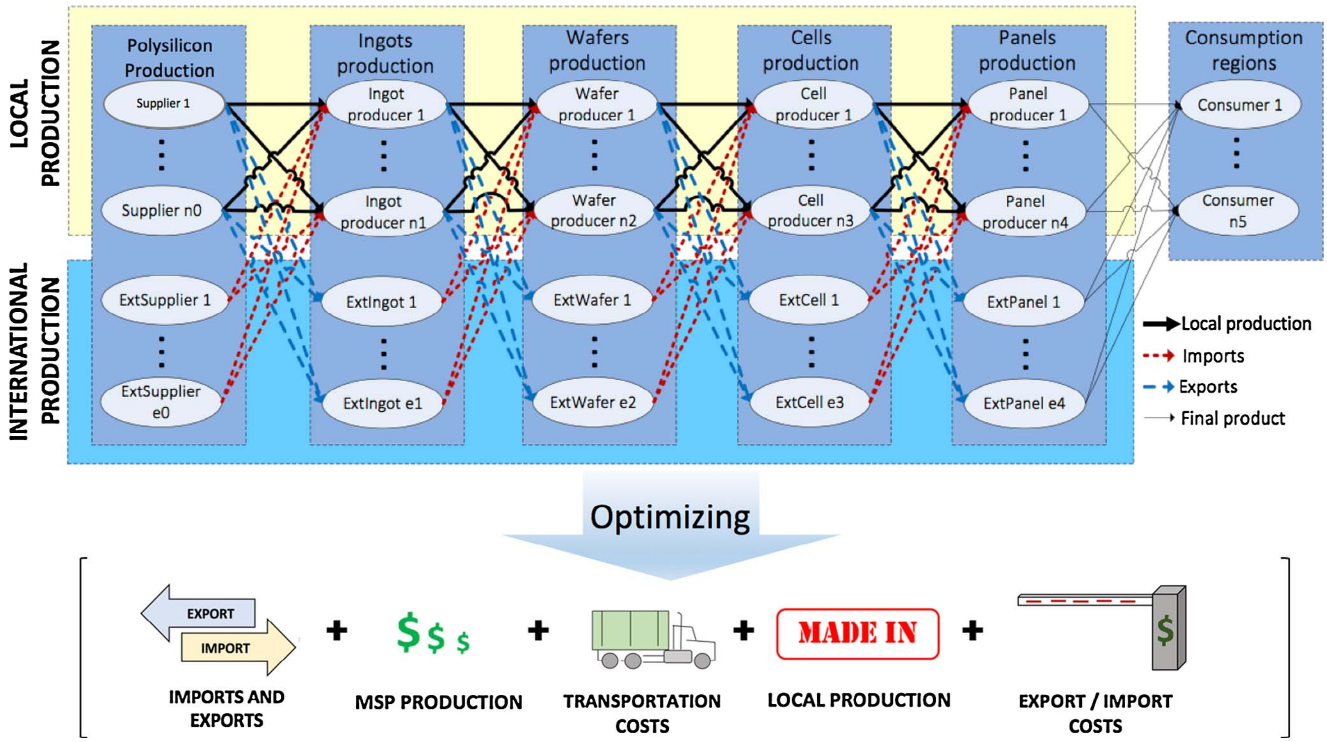

Fig. 1. Superstructure of the mathematical programming approach modeling the supply chain segments and the interactions between local and international production of goods for a given segment.

2.3. Transportation model

Transportation of goods between production locations at each segment of the PV value chain is assumed to be through highway systems when ground-based, and in shipping containers when transported across oceans. Maximum allowable capacity and cost per unit of transport is extracted from industry quotes, and transportation time is neglected for simplicity in this study.

2.4. Integrated framework: Supply chain optimization model (TIT-4-TAT)

The "Techno-economic Integrated Tool For Tariff And Transportation" (TIT-4-TAT) framework presented herein integrates state-level and country-level resolved MSP calculations, and couples them with a transportation and tariff analysis to optimize an entire supply chain, subject to different objectives, and contemplating scenarios where tariffs can be imposed and reciprocated between countries.

The framework superstructure is shown in Fig. 1. The five manufacturing stages in the PV supply chain corresponding to polysilicon, ingot, wafer, cell and module production are shown interconnected to one another, representing a continuous flow of goods. To satisfy demand, each of the five manufacturing stages contemplates two options: producing locally, and/or using an external node, representative of an international substitute production site. Local production stages are identified as n_0 for polysilicon, n_1 for ingots, n_2 for wafers, n_3 for cells, and n_4 for modules. International, or external production nodes are represented by e_0 for polysilicon, e_1 for ingots, e_2 for wafers, e_3 for cells, and e_4 for modules. The total manufacturing process flow ends at a sink node, labeled as 'Consumption regions'. Consumption regions are either local or international, depending on the focus of the country being analyzed.

2.4.1. Manufacturing stages

The modeling of the solar PV manufacturing supply chain contemplates several equations to account for the interaction between the local production nodes (n_0, n_1, n_2, n_3, n_4) and the international nodes (e_0, e_1, e_2, e_3, e_4). To ensure flow continuity of the processed materials, each manufacturing stage integrates a mass balance that equates the received goods to be processed, to the inventory levels plus the output processed good. This conservation criteria applies for the local nodes n_0 through n_4. In the case of the first stage, polysilicon production, n_0, the incoming raw material is silica. Ingot production node, n_1, utilizes polysilicon as its input to output ingots. Similarly, n_2, n_3, and n_4, receive ingots, wafers, and cells, respectively as inputs. International nodes are affiliated with all manufacturing stages: e_0 represents international polysilicon producers, e_1 international ingot producers, and e_2, e_3, e_4 international wafer, cell, and module producers, respectively.

2.4.2. Supply chain components

Supply chain components such as inventory levels, transportation of goods, limits on exports, limits on imports, transportation costs, limits on transportation volumes, economies of scale, and limits on internal production volumes are all accounted for, and mathematically described in the Appendix 1 in Supplementary Information.

2.4.3. Multi-objective solution approach

The mathematical programming formulation to be applied on the supply chain is composed of several objective functions that can be either maximized or minimized, depending on the stakeholder's main goal. These objective functions, described in Table 1, are (i) cumulative minimum sustainable price, (ii) transportation cost to export, (iii) import costs, (iv) local manufactured goods, (v) local transportation costs, and (vi) transportation costs to consumption regions.

For the case where multiple objective functions exist, the tradeoff between various objectives can be obtained with approaches such as the generation of a Pareto curve, developed with a multi-objective approach. However, as reported by [57], the generation of a Pareto curve has two main drawbacks. First, the final choice is taken only by a single decision-maker, which does not represent realistic scenarios where multiple parties are involved in a decision-making process. Second, the complexity of creating a Pareto front increases exponentially with the

Table 1
Summary for objective functions.

Variable	Objective	Rationale
Cumulative minimum sustainable price	Minimize	Increase competitiveness.
Exports transportation costs	Minimize	Promote local manufacturing and consumption; Reduce transportation emissions and airborne pollutants.
Import costs	Minimize	Increase local consumption; Reduce transportation emissions and airborne pollutants.
Local manufactured goods	Maximize	Promote local manufacturing and consumption.
Local transportation costs	Minimize	Reduce internal transportation cost; Reduce transportation emissions and airborne pollutants.
Transportation costs to consumption regions	Minimize	Satisfy demand for local product by being near to consumption regions.

number of objectives being considered.

To overcome these shortcomings, we follow the methodology from [58] which simultaneously accounts for the priorities from multiple stakeholders and objectives, without computing the full Pareto set. The multi-stakeholder approach is preferred over a multi-objective one (e.g., Pareto curve) given that the solution compensates simultaneously all the considered objectives.

This methodology proposes the introduction of a general objective function which weights the different objectives being proposed by the stakeholders. This weighted function, shown in Eq. (1), establishes that the compromise function, CS_i, is equal to the sum of a significance weight for each objective function, $w_{ij}^{ObjFunc}$, multiplied by a normalized function for each one of the main objective functions, $ObjFunc_j^{Normalized}$. The value or significance of the weight depends on the stakeholders' interests and main objective functions.

$$CS_i = \sum_j w_{ij}^{ObjFunc} \cdot ObjFunc_j^{Normalized}, \forall\ i \in StakeolderInterest \tag{1}$$

The difference between the "worst value" and the "obtained value" for each of objective function described in Table 1 is calculated. This difference is then divided by the difference between "upper bound" and "lower bound" of each objective function. This ratio represents a normalized value for the objective function, since the numerator refers to the difference between objective function value and the worst possible value, while denominator indicates the total possible range in which objective functions can be found, as detailed in Eqs. (2)–(7).

$$ObjFunc_j^{Normalized} = \frac{{}^{Upper}MSP^{global} - MSP^{global}}{{}^{Upper}MSP^{global} - {}^{Lower}MSP^{global}}, \forall\ j = CummulativeMSP \tag{2}$$

$$ObjFunc_j^{Normalized} = \frac{{}^{Upper}TC^{Exports} - TC^{Exports}}{{}^{Upper}TC^{Exports} - {}^{Lower}TC^{Exports}}, \forall\ j = TransportationExport \tag{3}$$

$$ObjFunc_j^{Normalized} = \frac{{}^{Upper}C^{Imp} - C^{Imp}}{{}^{Upper}C^{Imp} - {}^{Lower}C^{Imp}}, \forall\ j = ImportsCost \tag{4}$$

$$ObjFunc_j^{Normalized} = \frac{G^{TotalProcessed} - {}^{Lower}G^{TotalProcessed}}{{}^{Upper}G^{TotalProcessed} - {}^{Lower}G^{TotalProcessed}}, \forall\ j = LocalGoodProduction \tag{5}$$

$$ObjFunc_j^{Normalized} = \frac{{}^{Upper}C^{LocalTransp} - C^{LocalTransp}}{{}^{Upper}C^{LocalTransp} - {}^{Lower}C^{LocalTransp}}, \forall\ j = LocalTranspCost \tag{6}$$

$$ObjFunc_j^{Normalized} = \frac{{}^{Upper}TC^{ConsumpReg} - TC^{ConsumpReg}}{{}^{Upper}TC^{ConsumpReg} - {}^{Lower}TC^{ConsumpReg}}, \forall\ j = TranspConsumpRegions \tag{7}$$

The amount of compromise solutions, CS_i, will depend on the amount of values for $w_{ij}^{ObjFunc}$, as seen in Eq. (1), where each objective function is analyzed with different weight. It is, however, possible to obtain a compromise solution value without any specific preference in compensating differently all considered objectives, CS_i^*, in which case, all $w_{ij}^{ObjFunc}$ have the same value.

To report a compromise solution with equal weightings, a second step is introduced. This compromise solution is obtained by minimizing the objective shown in Eq. (8), $Obj^{SecondStep}$, which consists in the absolute value of the difference between the average of all the compromise solutions for all weights (*i.e.,* desired solutions), and the obtained solution. The value CS_i^* represents a manufacturing supply chain with the optimal compensation for the main objectives being considered.

$$Obj^{SecondStep} = ABS\left[CS_i^* - \frac{\sum_i CS_i}{I}\right] \tag{8}$$

Eq. (8), is a discontinuous function discretized into two parts. First part relates to the cases when the differences between CS, CS_i^*, and the average CS, is lower than zero. The second part considers when this difference is greater than zero. In order to find the best compromise solution, Eq. (8) is minimized to try to bring the compromise function closer to the desired compromise solution (average).

Fig. 2 shows a simplified representation of the multi-stakeholder approach process, consisting on four steps: (1) Data are input to the mathematical approach; (2) the conflicting objective functions are reformulated to generate a new objective solution that considers all individual objective solutions. This new objective function is called "compromise solution" (see Eq. (1)); (3) compromise function depends on each individual objective function that addresses different interests (e.g., financial, environmental) in a real-world case, and (4) final PV manufacturing supply chain takes into account values that are deemed acceptable for the objective of each stakeholder.

3. Case study for Mexico

3.1. General overview

Market research reports place Mexico among the world's top destinations for PV module manufacturing, given its access to demand [59] and PV technology adoption potential [60]. Mexico therefore represents an attractive location to develop manufacturing capacity to

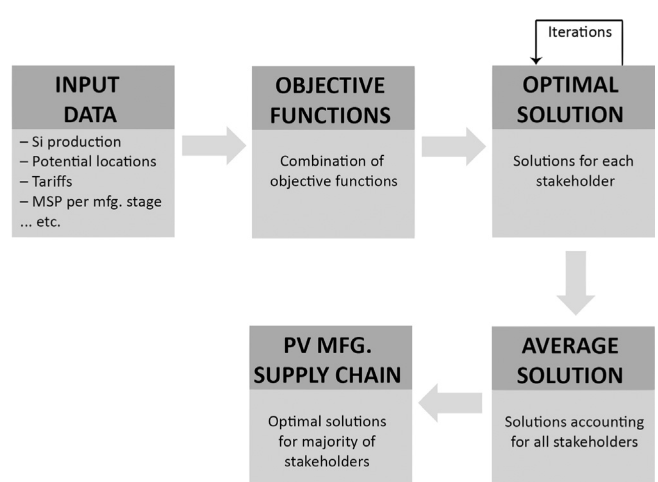

Fig. 2. General representation of the solution approach to solve the mathematical formulation.

strategically serve both local demand and that of the Americas [61].

Mexico is working to increase value chains, with a strategic focus on the energy sector [62]. The existence of successful advanced manufacturing industries in Mexico – including aerospace, electronics, and automotive – demonstrates the country's ability to produce complex, high-value goods. Therefore, possible knowledge spillovers from existing industries may be considered an incentive for government to support local manufacturing, and create relationships between the PV and other established industries across the country.

Local industry development can lead to strengthened supply chains and consolidation of industrial clusters, which have the positive attributes of agglomerating economies, increasing competitiveness and productivity, and enhancing knowledge spillovers; all while having both economic and sociopolitical benefits [63].

The economic benefits, however, can rapidly change in the context of a global market upon the introduction of protectionist measures. In fact, the decision of governments to reevaluate trade practices by other countries to determine potential sanctions in the form of trade restrictions (e.g., increased tariffs) have recently been on the rise [64,65].

In this case study, we model tariffs and interactions between Mexico and China as potential manufacturing sources, and Mexico, the USA, and Brazil as destinations. China is selected given its dominance in the world as a PV manufacturer, Brazil constitutes an emerging player in the Americas, and USA remains the main destination for Mexican products exports. The authors are cognizant that countries with similar or greater economic competitiveness characteristics –such as moderate wage growth, sustained productivity gains, and energy cost advantages [30]– also exist, and this framework can be applied to other regions, as well. It is important to note that the term 'global' is relative to a country of reference, which is Mexico in this case.

3.2. Models input data and assumptions

3.2.1. Cost model: Opex and capex

The cost model used for this analysis [56] was updated from its 2013 version in its cost components (see Supplementary Information). To mimic global tendencies of declining module prices, capital expenditure (capex) values such as property and land were assumed to be 20% less on the equipment costs of the reported values in [54,55] to simulate conditions for Mexico, and 50% less for both equipment and facility to simulate conditions in China.

We recreate MSP curves for all segments modeled in Mexico following economies of scale curves reported in the supplementary material of [55], as illustrated in Fig. 3. In the case of polysilicon and ingot, where no curves are documented, wafer MSP curves are used as a scaling baseline. Furthermore, a decomposition of the curves into piecewise linear segments is carried out for all manufacturing segments to avoid nonlinear and nonconvex relationships.

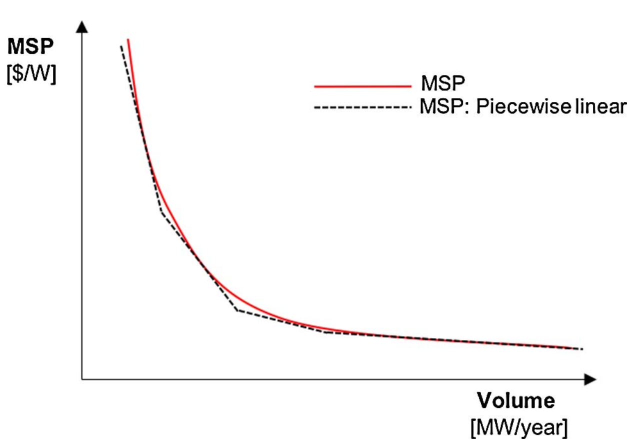

Fig. 3. Representation of a piecewise linear relation between MSP ($/W) for a specific manufacturing segment, and its production volume (MW/year). These curves are replicated for all five PV value chain segments, with manufacturing capacities ranging between 1 and 10,000 MW/year.

3.2.2. Tariffs

Import and export tariffs for goods coming in and out of Mexico were obtained from government sources [66]. Tariff code 8541.40.01, which pertains to semiconductors and photo-sensible devices, would apply to PV modules and solar cells; tariff code 7104.10.01, assigned to quartz-related goods, could apply to polysilicon, ingots, and wafers. Average duties for Brazil, China, USA, and Mexico, can be found in [67], and in this study are assumed to be as shown in Table 2. It is important to highlight that to create supply and demand distinctions, we have grouped China and Mexico as supply markets, and Mexico, USA, and Brazil as final demand markets, or consumption regions.

Scenario 1 represents a situation where no tariffs are set in place between countries on any final produced good of the PV value chain (*i.e.*, free trade agreements). Scenario 2 describes a case where import duties escalate and are reciprocated between countries either by trade agreements re-structuring, or anti-dumping measures, in line with plausible events [68,69].

In terms of manufacturing capacity, imported goods should be lower than an allowable import factor, β_{LD}^{LD}, which is set at 30% and is multiplied by the total received material for a local manufacturing node. The percent of goods sent to global manufacturing nodes (at any stage), δ_{LO}^{LO}, is set at 90%, and is multiplied by the product amount to be exported. Equations for imports and exports relations are presented and parameters, β_{LD}^{LD}, and, δ_{LO}^{LO}, are detailed in supplementary material.

3.2.3. Spatially-resolved state information

To create distinctions at the state level, we break down three elements which can vary geographically and are of significance in a balance sheet: electricity prices, weighted average cost of capital (WACC), and labor costs.

Average state electricity prices are obtained from government reported values used in Mexico's program for the development of the electric sector [70]. These are averages, varying between 0.104 and 0.129 $USD/kWh, and do not capture peak-demand charges. Labor wages, which are nationally homogeneous [71], are scaled based on the productivity of the manufacturing sector in each state, using the reported spread in Ref. [72]. This spread is used to rank-order states and create an evenly spaced cost multiplier ranging between values of 1.25 and 1.40, where highly productive states have a lower cost multiplier value. Lastly, the adherence to honor contracts at each state, also reported in [72], is taken as a proxy to modulate WACC and reflect inherent risks in capital access at each state. The range of WACC values reported in Ref. [73] for Mexico's technology manufacturing sector is used to rank-order states and apply an evenly-distributed value between 11.7% and 15.3%.

3.2.4. Transportation costs

Although several variables come into play when selecting a manufacturing site, to simulate national freight costs the geographic location of the capitals from the 32 existing states are assumed to be the optimal location for either the manufacturing or demand nodes. A python-based Maps Distance Matrix API is used to extract the highway distances between capitals for all possible permutations. This data is then weighted with vendor quotes that can transport the maximum allowed weight of 30,000 kg per truck, to obtain $/km per unit of merit (W or kg). Gasoline prices are assumed to be uniform throughout Mexico. Transportation of goods to the USA is assumed to occur through El Paso, TX, and to be delivered in Denver, CO, which we consider a centroid for the purpose of this study. International shipping costs from Shanghai, China to Manzanillo, Mexico are obtained from [74], and corroborated via quotes from different vendors. Shipping to Brazil is scaled from this value.

Table 2
Tariffs between analyzed countries for two distinct scenarios.

Country interactions (when A imports from B)	Average *ad valorem* import rights (tariffs) [%]									
	Scenario 1: No tariffs					Scenario 2: High tariffs				
	Polysilicon	Ingots	Wafers	Cells	Modules	Polysilicon	Ingots	Wafers	Cells	Modules
Mexico – Brazil	0	0	0	0	0	0	0	0	0	0
Mexico – China	0	0	0	0	0	15	15	15	15	25
Mexico – USA	0	0	0	0	0	35	35	35	35	35
Mexico – Mexico	0	0	0	0	0	0	0	0	0	0
Brazil – Mexico	0	0	0	0	0	0	0	0	0	0
Brazil – China	0	0	0	0	0	30	30	30	30	30
China – Mexico	0	0	0	0	0	15	15	15	15	25
China – Brazil	0	0	0	0	0	30	30	30	30	30
China – USA	0	0	0	0	0	45	45	45	45	45
China – China	0	0	0	0	0	0	0	0	0	0
USA – Mexico	0	0	0	0	0	35	35	35	35	35
USA – China	0	0	0	0	0	45	45	45	45	45

3.2.5. Polysilicon production

To simplify the location of the initial polysilicon production nodes, polysilicon plants are selected in 9 states that currently have reported mining operations to extract quartz and related products (Veracruz, Sonora, Chihuahua, Zacatecas, Nuevo Leon, San Luis Potosí, Guanajuato, Puebla, and Michoacán) [75], as quartz is a required material for metallurgical grade silicon production. We assume that gases required for silane and polysilicon transformations are equally available throughout Mexico. The maximum availability of silicon to be produced at each plant is assumed to be 25,000 metric tons/year. With a utilization rate of 4.31 g of Si per watt conversion, the upper limit on polysilicon processed by plant is therefore capped at 5.8 GW.

3.2.6. PV modules consumption

Official Mexican government projections expect utility-scale PV installed capacity to reach 11.56 GW in 16 states within the next decade, under a high-penetration scenario [70]. A time frame of 7 years is assumed sufficient to accomplish the full expected deployment, with a yearly linear increasing function. With expected growth trends for the US market as reported in [76], and Latin America (Brazil), a fixed yearly demand of 4 GW, and 2 GW is assumed to be met by international competitive markets, respectively.

3.2.7. Computational resources

The complete model consists of 133,094 constraints, 112,444 continuous variables and 34,674 binary variables. The framework and scenarios are coded in General Algebraic Modeling System (GAMS) software, and solved with a CPLEX solver in a 2.9 GHz Intel Core i7 processor and 8 GB RAM computer.

4. Results

The TIT-4-TAT framework was used to simulate the countries' interactions in meeting expected growth in the demand markets, and solved in two stages. The first stage determined the upper and lower bounds for the different objective functions mentioned in Section 2.4. The second stage determines the CS function for each of the considered weights.

Given that different stakeholders might have different priorities for each of the objective functions described in Section 2.4, this methodology considers a weighting system to represent different priorities, whether financial or environmental. The 63 weighted scenarios are systematically solved to ensure a wide range of different objective priorities are covered. The algorithm to obtain each of the described weights is as follows: (1) Only one objective function is weighted, while weighting for remaining objective functions is equal to zero. (2) Two objective functions are weighted with the same weight (e.g., 0.5 each one) while others are equal to zero. (3) Three objectives are weighted, while others are held constant. (4) This process continues until all objective functions are weighted. In other words, when 2 objective functions are weighted, there are 15 options to select 2 objective functions from; which are all weighted. Similarly, when 3 objective functions are weighted, there are 20 possible combinations to be considered. Data for weights for each of the objectives functions are provided in Table S1 (Supplementary material).

For the first stage, depending on the objective function being analyzed, the central processing unit (CPU) time to solve ranged between 12 and 36 h. The second stage the CPU time to solve ranged between 20 min and 1 h depending on the scenario being studied (no tariffs and high tariffs). Difference in solution times came mainly from the initial values for variables provided upon upper and lower bounds calculations.

4.1. MSP without interacting markets

A color-coded map of Mexico is shown in Fig. 4 representing the MSP range at each of the 5 manufacturing stages, at an estimated 400 MW capacity. Brighter shades of green represent lower relative MSP, and darker shades represent relative higher values. These maps elucidate the states where Mexico is more attractive to develop specific segments of the value chain under the aforementioned assumptions, excluding state and municipal incentives, and without taking into account supply chain considerations nor optimal transportation routing. The lower bounds correspond to approximately \$0.13/W for polysilicon, and \$0.59/W for the cumulative sum of ingot, wafer, cell and module segments (total \$0.72/W). The upper bounds are calculated to be \$0.15/W for polysilicon, and \$0.65/W for the remaining value chain segments.

4.1.1. Scenario 1: No tariffs

The upper and lower bounds computed for each objective function during the first stage of the optimization process are shown in Table 3. These bounds, obtained through an optimization of each individual objective function (Section 2.4), determine the feasible space where an optimal and feasible solution can be found once the CS function is optimized under a 'No tariffs' scenario. The bounds are used to normalize values for individual objective functions defined in Section 2.4, and stated in Eqs. (2)–(7). The rationale for each variable and its optimal bound is described in Table 1.

There is a possibility that different objectives are fully satisfied (either maximized, or minimized) all while optimizing for an individual objective. Fig. 5 illustrates the level of satisfaction which other objectives attain while each individual objective is optimized to either its maximum, or minimum, as described in Table 3. Each radar plot shows

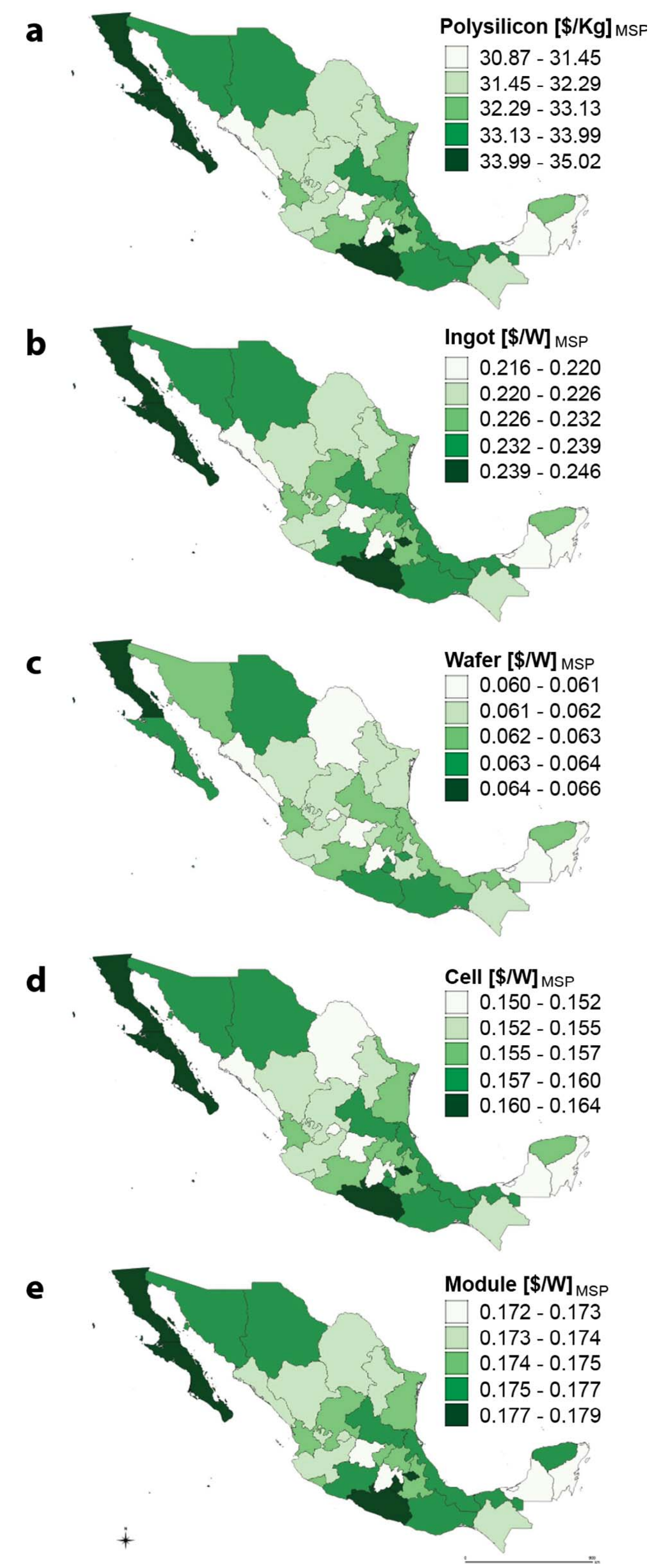

Fig. 4. MSP of (a) polysilicon, (b) ingot, (c) wafer, (d) cell, and (e) module production in different states in Mexico. Lighter shades of green denote a lower MSP value. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the main objective being optimized, which corresponds to one of the 6 objectives labeled on the left of Fig. 5. The outermost region represents 100% of satisfaction achieved in attaining the optimal value, while the closer to the center of the radar plot denotes a low satisfaction value.

Table 3
Summary for lower and upper bounds computed for the considered objective functions under the "No tariffs" scenario.

Variable	Objective	Optimal Value	Upper Bound	Lower Bound
Transportation cost for exports (Million $US)	Minimize	Lower bound	11335.6	0[a]
Import cost (Million $US)	Minimize	Lower bound	32918.7	0[a]
Cumulative MSP ($US/W)	Minimize	Lower bound	17.58	0.71[a]
Internal production (MW)	Maximize	Upper bound	2726716.86[a]	331.77
Internal transportation cost (Million $US)	Minimize	Lower bound	2893.10	0.001[a]
Transportation cost for consumption regions (Million $US)	Minimize	Lower bound	410.30	53.17[a]

[a] Desired objective.

A satisfaction level of 100% means that a given objective functions value is equal to the best value for this objective, while a satisfaction level equal to 0% denotes that a specific objective function has a value equal to its worst possible value. It is important to note that a value of 0% does not equate a value of 0 for the objective to be analyzed. For instance, a value of 0% for cumulative MSP represents that the cumulative MSP takes a value of $17.58/W (equal to its upper bound, though the optimal value is the lower bound), as observed in Table 3.

As an example, minimizing MSP generates a supply chain layout with high satisfaction values for internal transportation costs, as well as for exports, and imports costs, while simultaneously achieving low satisfaction values for internal production levels and transportation costs to consumption regions. In the case of maximizing internal production, the objectives for both internal production and transportation costs to consumption regions are highly satisfied, while the remaining objectives are not.

As previously described in Section 2, the CS approach tries to simultaneously optimize the greater amount of objectives at once (all, if possible). The satisfaction levels achieved for this proposed solution is shown in the blue radar plot of Fig. 5, and Table 4, where three objectives reach their maximum satisfaction, or optimal, value.

By translating satisfaction values into a general supply chain we generate Fig. 6, which shows three different solutions for comparison. Fig. 6a represents the local supply chain structure when the MSP is minimized, and where a considerable amount of polysilicon, ingots, wafers, and cells are imported while most of PV modules local demand is satisfied by external production. Fig. 6b represents the supply chain layout when transportation cost to consumption regions is minimized. In this case demand for finalized PV modules can be fulfilled by internal production, since the distance between Mexican production nodes to consumption regions is lower than the distance between international production nodes (China) to consumption regions. However, substantial amounts of goods are imported from external (international or global) suppliers, and a large amount of solar cells are exported in this processing stage.

Fig. 6c illustrates the general supply chain configuration for the proposed CS. The PV modules demand is satisfied by a combination of local and global production, and the imported amount of intermediate products (ingots, wafers, cells) is minimized. In this solution, 10% of the Mexican demand, 43% of the Brazilian demand and 100% of American demand of PV modules is satisfied by local (Mexican) production. It is important to note that for this case satisfying a local market (Mexico) or global market (USA and Brazil) are similar given the lack of tariffs; hence most of the PV modules are delivered to USA which is equivalent to a sink node with high demand.

It should be noted that based on the results shown in Fig. 5, the

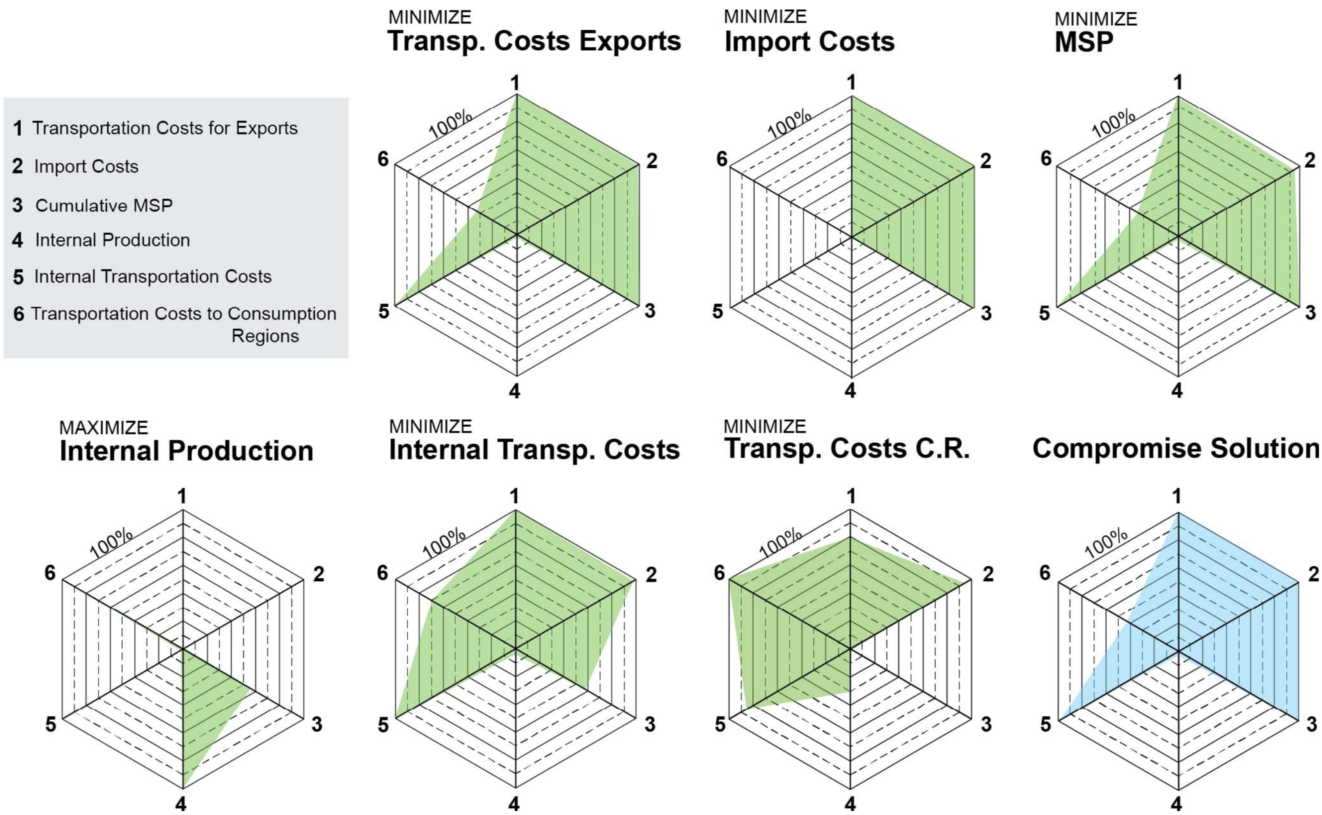

Fig. 5. Objective satisfaction when other objectives are optimized and import tariffs are not imposed.

solutions in Fig. 6a and c have the same value for the cumulative MSP (*i.e.,* they both met the MSP objective with 100%), which indicates that for the same optimal value for an objective function, different layout configurations can exist.

Fig. 7 describes the completely developed manufacturing supply chain for the proposed optimized CS, with only locations in Fig. 7a, and locations, volumes, and interactions, in Fig. 7b. In this case, each manufacturing segment is associated with a state location, selected by optimizing processing and transportation costs. Polysilicon production is done in Veracruz because this region has reported quartz availability, and is one of the initially suggested source nodes input to the model. The production of ingots, cells, and modules is carried out in states with low MSP values (Campeche and Quintana Roo), while wafer production is carried out in Nuevo León, which is not the state with the lowest MSP for that manufacturing segment. In the solution reported in Fig. 6b, the local production is sufficient to meet the full local demand, but the optimized supply chain configuration in Fig. 6c exports and imports PV modules to and from global consumption regions given the distances and null tariffs.

4.1.2. Scenario 2: High tariffs

Scenario 2 represents the modeling of relative 'High Tariffs' for the movement of goods across countries, as detailed in Table 2. The same approach as Scenario 1 is used to obtain upper and lower bounds for each objective function, as summarized in Table 5. The rationale for each variable and its optimal bound is described in Table 1.

Large deviations compared to Table 3 (Scenario 1) are observed in the variables related to exports and imports, as well as the lower bound for internal production. It is also noteworthy that the lower bound for MSP in the 'High Tariffs' scenario is more than 3 times the MSP value for the 'No tariffs' scenario.

Fig. 8 illustrates the level of satisfaction other objectives attain, while each individual objective is optimized to either its maximum, or minimum, as described in Table 4. Each radar plot shows the main objective being optimized, which corresponds to one of the 6 objectives labeled on the left of Fig. 8. The outermost region represents 100% of satisfaction achieved in attaining the optimal value, while the closer to the center of the radar plot denotes a low satisfaction value.

The satisfaction levels of the objectives met upon individual optimization can be seen to differ considerably from those levels shown in Fig. 5. For our proposed CS solution, there are 5 out of 6 objectives with satisfaction levels above 95% (close to 100%) in the 'High Tariffs' scenario, as shown in Fig. 8 and Table 6. Also shown in Table 6 is the value of 83.43% of satisfaction for the overall CS.

Table 4
Summary for the percent of satisfaction attained for each objective, and the values corresponding to that percentage under the "No tariffs" CS.

Objective	Weighting	Optimal Value	% of Satisfaction	Result in CS function
Transportation cost for exports (Million $US)	16.66%	Lower bound	100%	0
Import cost (Million $US)	16.66%	Lower bound	100%	0
Cumulative MSP ($US/W)	16.66%	Lower bound	100%	0.71
Internal production (MW)	16.66%	Upper bound	3.30%	90573.65
Internal transportation cost (Million $US)	16.66%	Lower bound	97.91%	60.27
Transportation cost for consumption regions (Million $US)	16.66%	Lower bound	42.47%	258.61
Compromise Solution Satisfaction (%)	–	–	73.94%	73.94

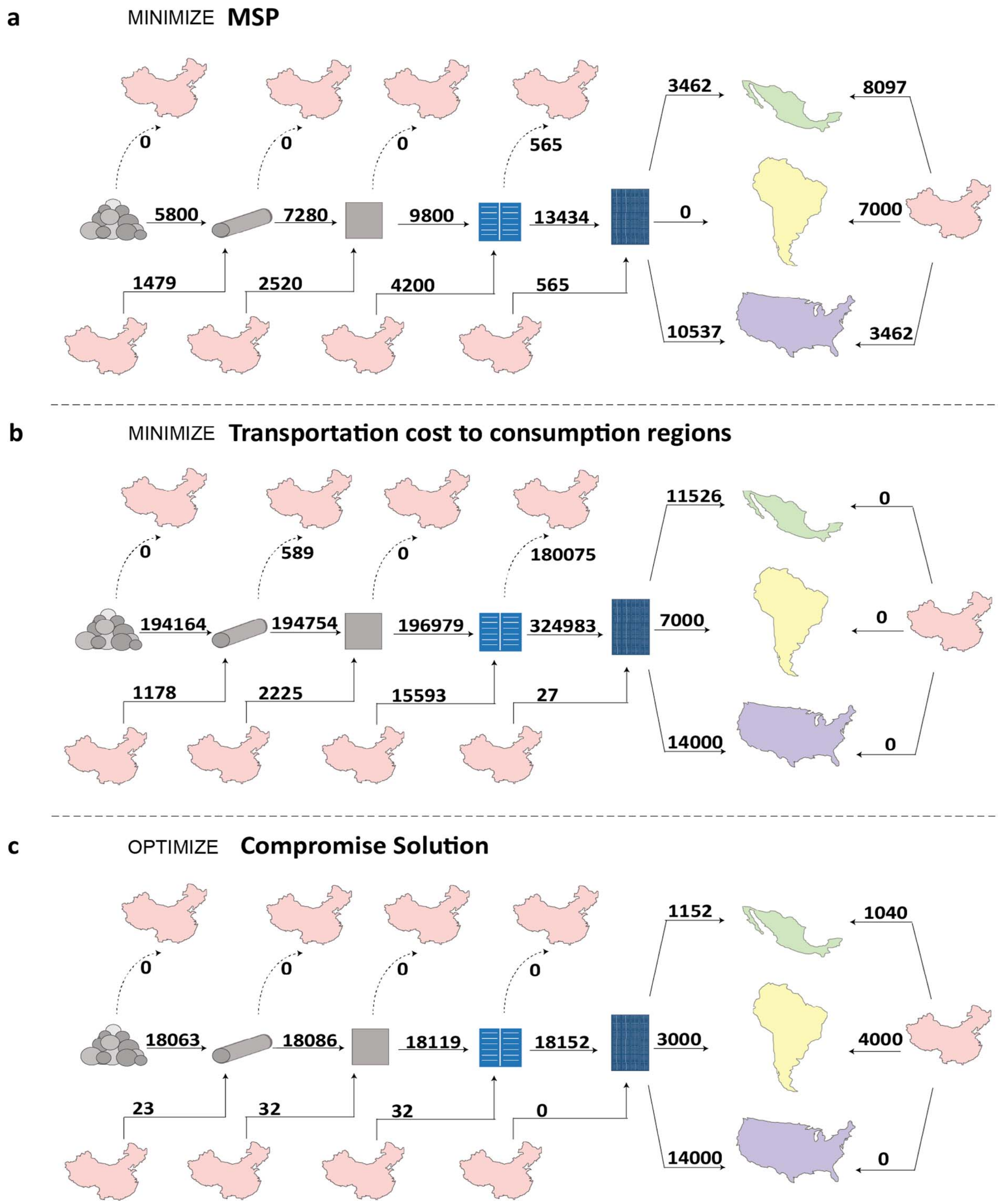

Fig. 6. General solutions representation for different cases. (a) MSP minimization, (b) Transportation costs to markets minimization, and (c) Compromise solution maximization (No tariff case). All units are in MW.

Similar to the case with null tariff, Fig. 8 provides a general representation of the supply chain volumes and interactions to and from Mexico.

Fig. 9a–c, correspond to MSP minimization, transportation cost to consumption regions minimization, and the proposed CS solution, respectively. Internal production is more than 30,000 MW in the same time horizon for the CS in this case; greater than the CS in the scenario with no tariffs. Solutions when transportation costs to consumption regions (Fig. 9b) and MSP are minimized (Fig. 9a) are very similar. However, minimizing transportation costs to markets results in higher internal production compared to the case where MSP is minimized, due in part to the higher import expenses occurring in the MSP minimization case. For the optimized CS (Fig. 9c), imports are minimized and there is no export activity at any manufacturing stage, and very minimal from international markets to meet local demand.

Fig. 10 describes the fully developed manufacturing supply chain for the proposed optimized CS under the scenario with high tariffs, with only locations in Fig. 10a, and locations, volumes, and interactions, in Fig. 10b.

The optimal geographical location of manufacturing plants is

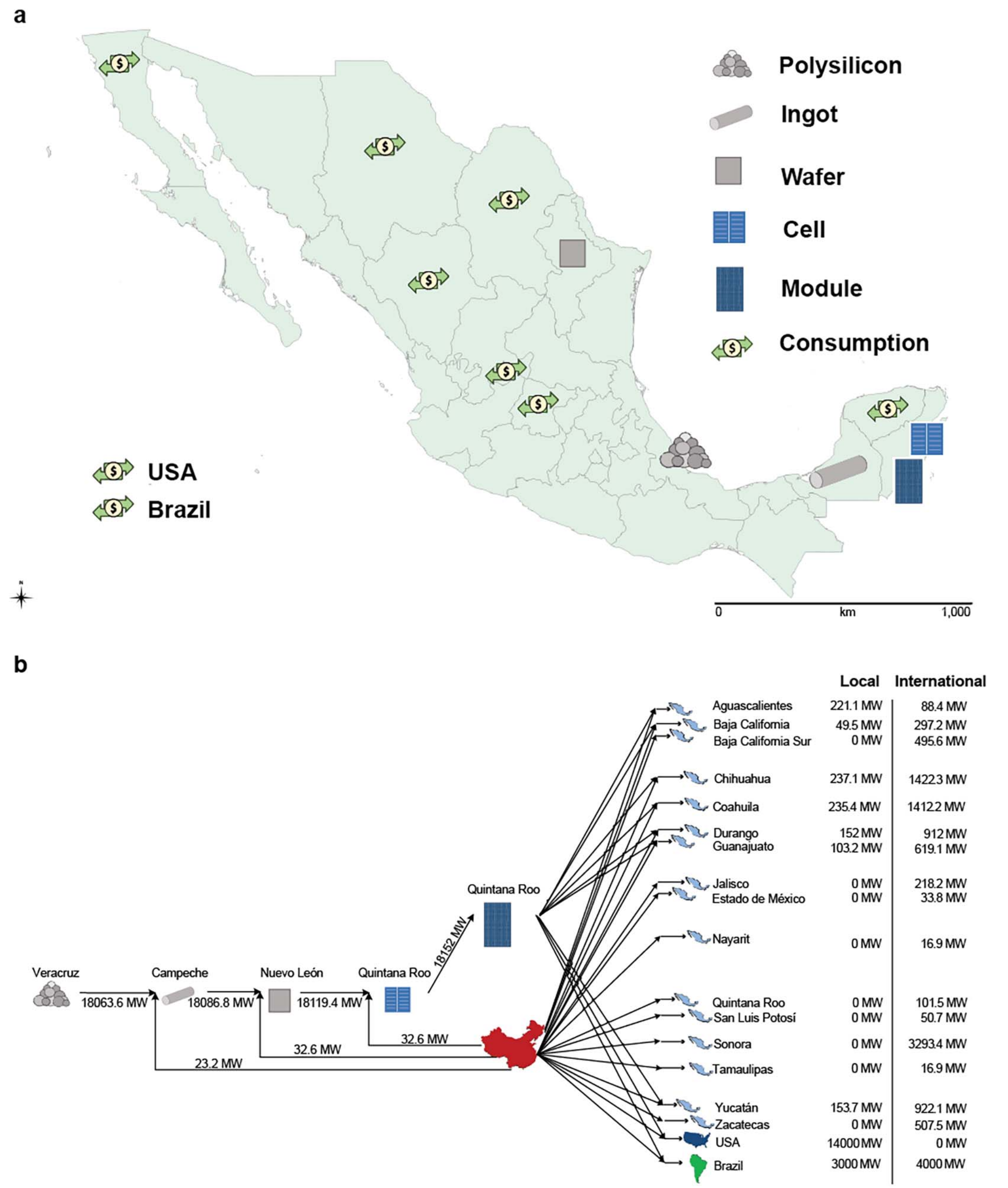

Fig. 7. (a) Geographic distribution of supply chain facilities for the "No tariffs" scenario in Mexico. (b) Detailed layout for the entire supply chain and manufactured capacities under "No tariffs" scenario.

Table 5
Summary for lower and upper bounds computed for the considered objective functions under the "High tariffs" scenario.

Variable	Objective	Optimal Value	Upper Bound	Lower Bound
Transportation cost for exports (Million $US)	Minimize	Lower bound	8051.4	0[a]
Import cost (Million $US)	Minimize	Lower bound	5213.5	15.9[a]
Cumulative MSP ($US/W)	Minimize	Lower bound	17.06	2.24[a]
Internal production (MW)	Maximize	Upper bound	2258016.97[a]	40956.41
Internal transportation cost (Million $US)	Minimize	Lower bound	2498.58	0.144[a]
Transportation cost for consumption regions (Million $US)	Minimize	Lower bound	252.61	70.73[a]

[a] Desired objective.

strongly affected by the set of tariffs imposed by different countries. Fig. 10a renders the optimal location for each manufacturing segment, selected by optimizing processing and transportation costs under the tariffs described in Table 2. Polysilicon production is carried in Puebla, which is one (out of 9) candidates selected given its reported quartz availability, and also relates to the lowest MSP values calculated. Ingot production is located in Quintana Roo, and wafer manufacturing in Sinaloa; both states associated with low MSP, as shown in Fig. 4b and c, respectively. Three different states are selected for processing cells: Nuevo León, Guanajuato, and Querétaro. A significant number of sites

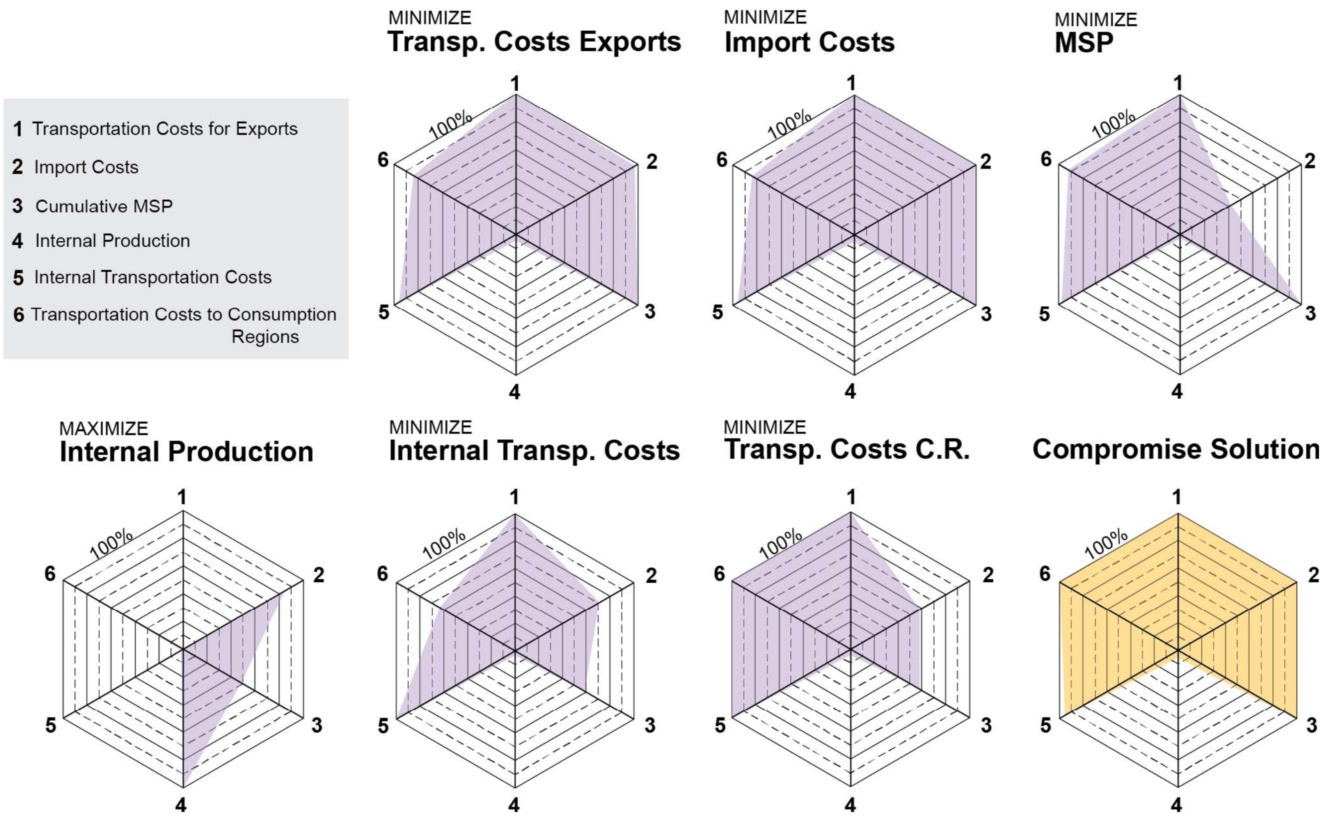

Fig. 8. Objective satisfaction when other objectives are optimized and import tariffs are imposed.

for module manufacturing are observed in this case, with a total of 8 across different regions. Fig. 10b shows that demand for PV modules is mainly met by local production, while international suppliers can still meet local demand, either partially (Jalisco, Nayarit, Zacatecas) or fully (Tamaulipas). Also, international suppliers provide a small fraction to meet US market demand. This supply chain layout is diversified to satisfy the most objectives possible, as stated earlier and under a case scenario with high relative tariffs imposed.

5. Discussion

5.1. Framework elucidates complex interactions

Through our TIT-4-TAT framework, interactions among countries in the PV manufacturing sector are modeled. Supply-chains are captured by incorporating (i) geographical layout within all the states in Mexico, and (ii) exchange between Mexico and China for the goods where it is more economically feasible to import from China, rather than to manufacture in Mexico. These dynamics are shown to grow in complexity (Figs. 7b and 10b) when supply and demand in modeled markets are subject to different objectives and trading constraints.

For the two tariff scenarios herein proposed, we include the same 6 distinct objectives to better mimic the decision-making process which policy makers are often subject to, where many different goals are usually at stake and optimizing for one can significantly impact others. The compromise that must be made between different objectives will depend on the risk appetite of the stakeholders, and the potential impact on the end customers or constituents. For our demonstration we limit ourselves to assign equal weights to each objective function, although these weights can be tuned to simulate a geography of interest. We remark that supply chains need to be incorporated to design better policies focused on clustering, innovation, and other portfolios of direct/indirect incentives, and that isolated manufacturing analyses that do not consider the potential to interact with other geographies may not be well suited to determining the optimal manufacturing locations, commensurate with realistic globalized scenarios.

Our analysis shows that values for an objective function can widely differ upon the introduction of supply chain characteristics, such as transportation and tariffs. Evidence of this can be drawn in the case of MSP, which is shown both in an isolated way (Fig. 4), and in a broader dynamic context (Figs. 7 and 10). For example, Nuevo Leon is a state that, when taking into account supply chain interactions, is recommended as a manufacturing site for the manufacturing of wafers (no tariffs) and cells and modules (high tariffs), despite not having the

Table 6
Summary for the percent of satisfaction attained for each objective, and the values corresponding to that percentage under the “High tariffs” CS.

CS variable	Weighting	Optimal Value	% of Satisfaction	CS result
Transportation cost for exports (Million $US)	16.66%	Lower bound	100%	0
Import cost (Million $US)	16.66%	Lower bound	99.99%	16.33
Cumulative MSP ($US/W)	16.66%	Lower bound	100%	2.24
Internal production (MW)	16.66%	Upper bound	5.38%	160375.68
Internal transportation cost (Million $US)	16.66%	Lower bound	95.44%	113.99
Transportation cost for consumption regions (Million $US)	16.66%	Lower bound	99.71%	71.25
Compromise Solution Satisfaction (%)	–	–	83.42%	83.42

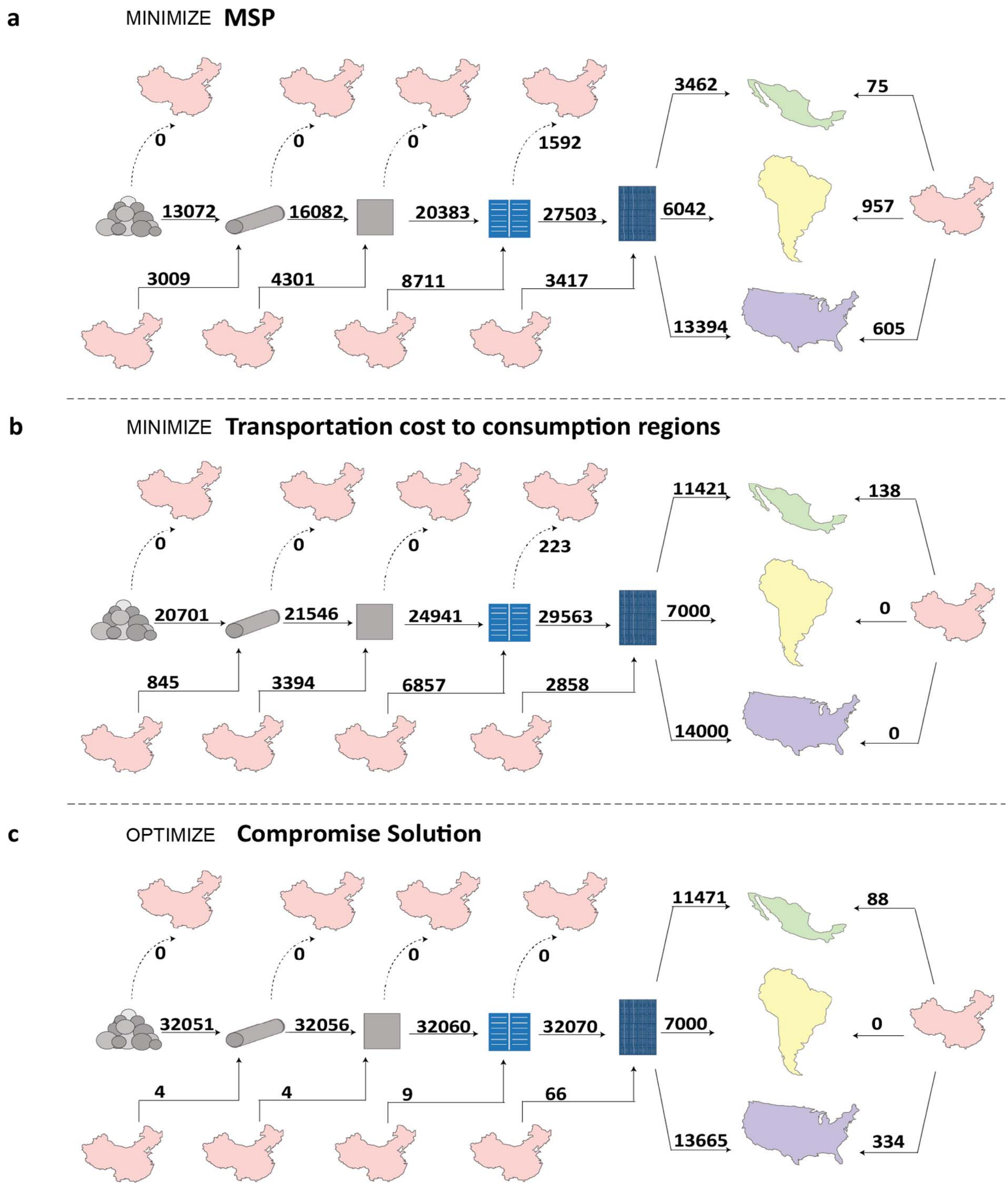

Fig. 9. General solutions representation for different cases. (a) MSP minimization, (b) Transportation costs to markets minimization, and (c) Compromise solution maximization (High tariff case). All units are in MW.

lowest MSP values on those segments, as seen in Fig. 4. This difference holds true for both tariff scenarios, and can be attributed to the multi-stakeholder optimization nature of the proposed approach.

5.2. Role of tariffs

The comparison between high and no tariff scenarios allows us to evaluate the impact of protectionist measures on different variables, or objective functions. A variable of interest is the locally manufactured volume. Under a high tariff scenario, the local manufacturing production is seen to increase substantially in the optimized CS by 70% at each manufacturing stage, approximately, compared to the no tariffs scenario. This could prove attractive if the goal is to spur short-term employments, which would contrast with the high-capex, long-term vision required for investments in this manufacturing industry.

MSP is observed to affect the configuration of internal supply chain interconnections, however the main driver for re-configurations of supply chains in global markets is the tariff levels imposed between countries. This is seen when comparing Figs. 7 and 10, where the number of interactions between nodes and the production volumes drastically change when varying tariff levels.

When evaluating the impact of tariffs, we also observe an increase in

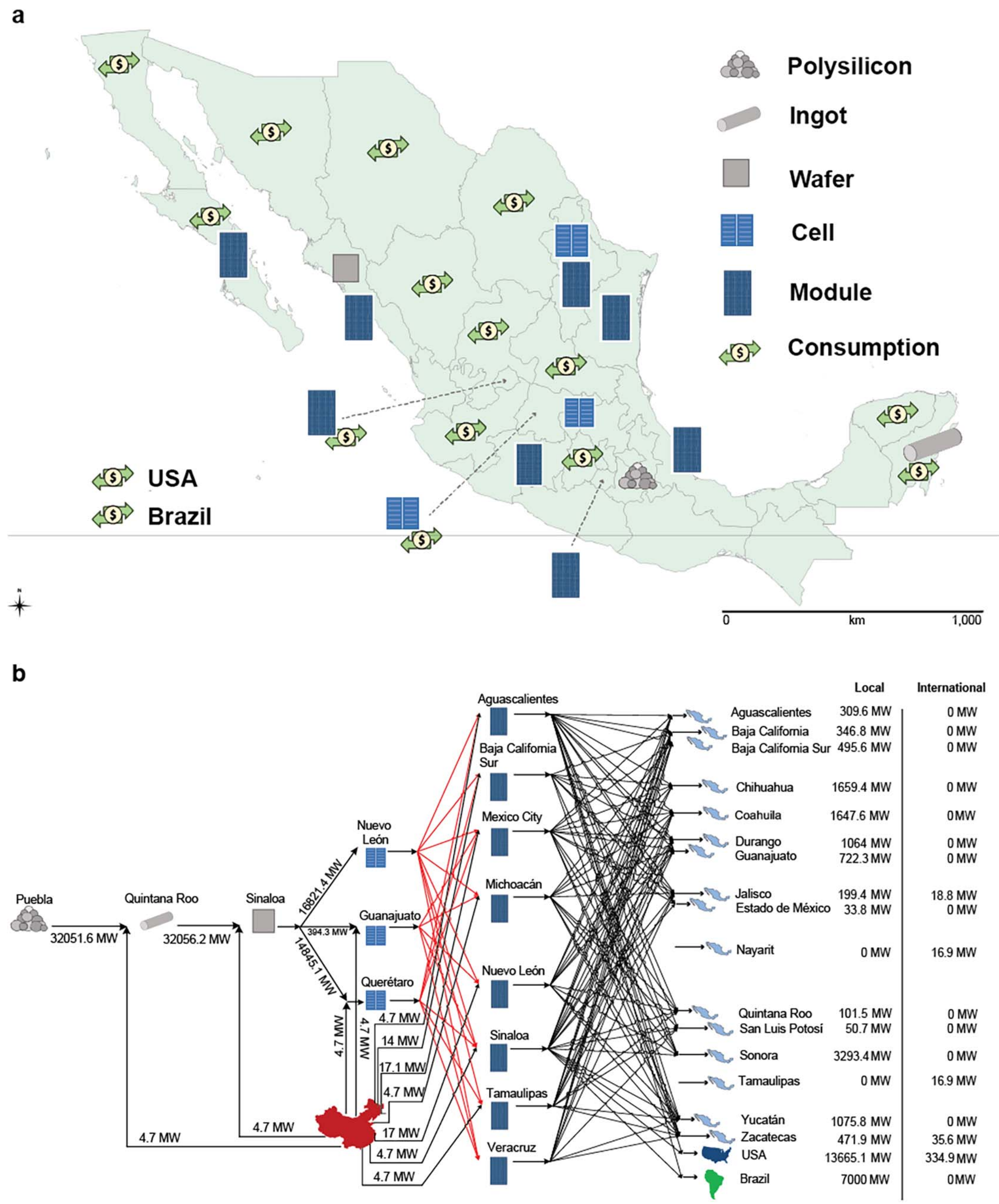

Fig. 10. (a) Geographic distribution of supply chain facilities for the "High tariffs" scenario in Mexico. (b) Detailed layout for the entire supply chain and manufactured capacities under "High tariffs" scenario.

some values that can closely track PV penetration, such as the MSP, herein considered a proxy for retail price. Despite the CS fully satisfying more objectives in the high tariff scenario (Fig. 8), the resulting MSP for the final module manufactured in Mexico is forbiddingly high when set in a realistic context: a difference of more than 200% between the optimized MSP values for both tariff case can be calculated from Tables 4 and 6. A closer look into these MSP values show that the lowest MSP possible was obtained for both tariff scenarios. Given that no further variations were introduced in the model, and that the model optimized to the lowest possible MSP values, we conclude that differences in MSP values can be attributed only to the addition of tariffs between countries at different segments of the value chain.

This is particularly relevant from the perspective of incentivizing PV deployment to achieve TW-scale penetration [77,78]. Our results indicate that introducing tariffs between countries is shown to significantly alter the MSP, which in turn renders a more expensive final good, and in consequence, can hinder the adoption rates required to mitigate climate change [57]. In other words, if a tariff war were to occur over different countries as modeled in the 'High tariff' scenario, the end result would be a significantly more expensive good to the end consumer; the comparative advantages gained when intermixing economies would diminish, increasing prices, and slowing the adoption of solar PV. It is expected that solar PV installations would suffer in countries where the manufacturing goods are more expensive in comparison to other countries, and a disruption in demand dynamics might result in oversupply conditions for the remaining countries.

The implications of these results, quantified for these scenarios, appear consistent with results from other studies [79] which state that more companies would tend to support open trade when their supply chains have global interactions to minimize costs, and by consequence, price. In this study, this can be explained mainly by the competitive MSP optic: assuming equal capital structure, companies that are locally

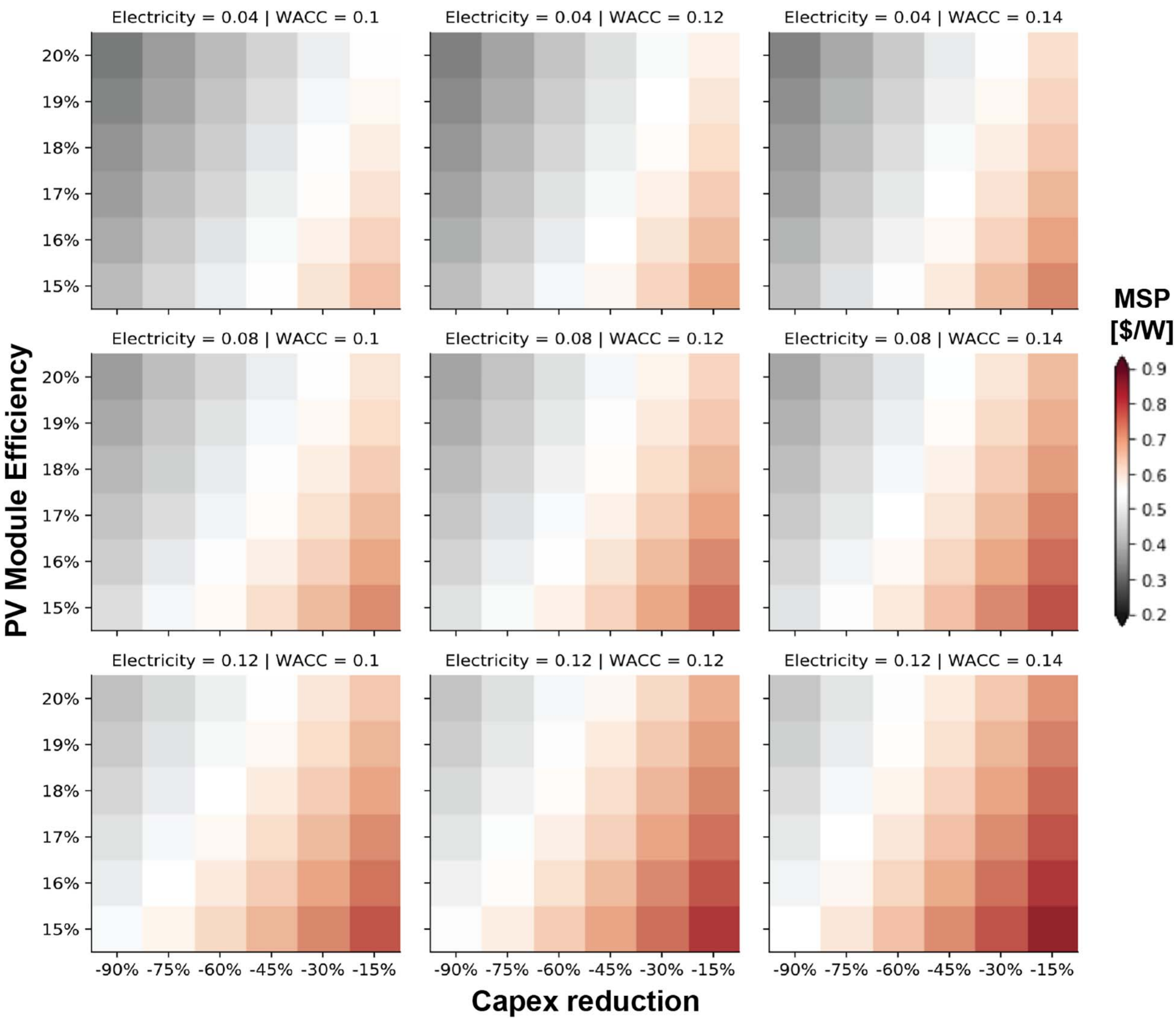

Fig. 11. MSP ($/W) as a function of capex reduction and efficiency gains at the module level. Each block contains MSP value for a given Electricity price, and WACC, ranging from $0.04–0.12 kWh^{-1}, and 10–14%, respectively.

established and can interact with other supply markets can manufacture and deliver goods at lower MSP under a no tariff scenario, than under higher imposed tariffs. Linking these findings with the goals of a policymaker, the value of a decarbonized electricity sector (due to high PV penetration) must be weighed against created jobs that might result as a protectionist measure is introduced, which would be potentially limited as no market would sustainably absorb an overpriced commodity. Considering tariffs as a variable that cannot be significantly changed by companies (assuming negligible lobbying power), and potentially not an appealing one to increase by any country without substantial merits, other approaches that can enable local manufacturing while reducing MSP are discussed below.

5.3. Manufacturing and competitiveness outlook

It is important to highlight that current competitive conditions for manufacturers are considered to be difficult to thrive under, and several reports have indicated that many manufacturers may be selling at a loss, or with thin profit margins [80,81]. However, the need to maintain the ability to respond quickly to market changes, as well as to reduce supply chain costs, persists.

Besides some of the main differentiators in manufacturing between China and other countries, such as supply-chain advantages (equipment and material discounts) and scale, as described in [55], there are other notable variables that can be influenced within a region to become more competitive. These drivers are (1) electricity reduction, (2) WACC reduction, (3) module efficiency increase, and (4) capex reduction. For the case of Mexico, the interplay of these different variables with MSP is shown in Fig. 10.

Fig. 11 is a collage of contour plots for instances where electricity prices, WACC, efficiency levels for PV modules, and capex reductions (baseline values taken as 100% from [29]) are shown. Red color denotes high MSP, and dark gray represents MSP $<$ 0.2 $USD/W. These variables are thought to be country-driven (electricity prices, WACC), and manufacturers innovation potential (capex reduction, efficiency levels). Authors have proposed strategies to address these issues, and can be synthesized as:

1. *Electricity reduction:* Through recently-enacted energy reforms in Mexico, electricity prices are expected to decline. Ensuring a mix of optimal generation plants that can translate into low prices without compromising clean energy targets, nor increasing pollution levels, is of fundamental importance to reduce MSP levels and ensure higher PV adoption.
2. WACC reduction: As described by [82], WACC is strongly affected by the scarcity of capital, inflation rate, demand for credit, and relative supply and demand of finance, among others, resulting in higher interest rates. Proper conditions for equity and debt markets

to reduce their perceived risks on their investments in Mexico will allow for companies to reduce their MSP by lowering their required IRR.

3. *Efficiency increase:* Higher yields and efficiency through technology innovation can be systematically approached starting with high-quality material growth methods that minimize defect nucleation and propagation through processing steps [15].
4. *Capex reduction:* Reducing capex in the PV industry has been proposed to be achieved through different approaches, like increasing manufacturing throughput and streamlining operations, among other options [83].

Our results show that optimal manufacturing conditions usually lead to manufacturing sites producing at irregular intervals over different time periods, to attain the highest satisfactory levels on most objective functions. As an example, Figs. 6b and 9b denote the varying levels of manufacturing at each of the sites. Under conventional financing approaches, obtaining the capital to build a plant with highly varying levels of manufacturing can become highly unattractive for investors who require a steady return on their investment. This, however, opens a new market for flexible production tools, or repurposing of existing infrastructure, which can lead to lower capex investments, as previously suggested in [16]. Innovation in new manufacturing technologies can significantly reduce the costs, too [16,55,78,83]. As our results show, manufacturing volumes are maximized in order to reduce the compromise solution objective, pointing towards increasing scale as a strategy to reduce MSP, as [55] estimate.

Other variables that are captured in the model and have the potential to reduce MSP and strengthen supply chains are lower transportation costs (good quality infrastructure), increases in labor productivity, and scale achievement through patient capital. Variables that are not captured in this model, and which play an important role, are access to materials, transportation times, and knowledge spillover benefits.

6. Conclusions

In this contribution we presented a framework, TIT-4-TAT that couples a techno-economic model with a mathematical programming transportation algorithm to optimize supply chain layouts for PV manufacturing under equally weighted objectives. The effect on PV manufacturing upon varying import tariffs between countries is studied. We observe that in order to optimize for the least-cost production –and therefore the highest deployment opportunity– while insightful by itself, a MSP value should be considered in a network context when developing geographically-oriented strategies. Our analysis suggests that tariffs and transportation costs can highly impact decisions as to optimally siting a manufacturing plant, and is shown to increase MSP by 200% under our studied scenario.

Given the inherent uncertainty in modeling a firm's true manufacturing cost and capital structure, paired with accelerated changes that have led to substantial declines in average selling prices [84,8], we believe the strength of our model lies in its flexibility to be continuously updated to best reflect the latest conditions deemed representative. At the time of this publication, spot prices for PV grade polysilicon were close to half of our modeled MSP estimates [84], which leaves room for a refined modeling of this segment, and therefore achieving a lower cumulative MSP than the ones herein calculated.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2017.12.047.

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